Long-Term Aging of NO_x Sensors in Heavy-Duty Engine Exhaust

by
John Orban
David Wendt
(Battelle)

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APBF-DEC Participants

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Ford
GM
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Lubrizol
Marathon Ashland
Motiva
NPRA
Pennzoil-Quaker State
Shell Global Solutions
Valvoline

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- Testing Lab Project Leaders
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  - Chris Sharp (SwRI)
- NO_x Sensor Supplier
  - NGK Insulators

Study Objectives

- Demonstrate the Performance and Durability of NO_x Sensors During 6,000 Hours of Operation
  - Engine-Out (up to 600 ppm)
  - Post Catalyst (up to 250 ppm)
  - Steady-State (13 ESC modes)

Study Questions

(NO_x Sensor Study)

1. How well do the NO_x sensor voltages correlate with the NO_x analyzer readings?
2. What is the relationship between NO_x sensor voltages and NO_x analyzer readings at a given location? Does it change over time or by mode?
3. Are there systematic changes in sensor performance (overall or at a given sensor location)?
4. How often do sensors need to be recalibrated?
5. What is the expected lifetime of the NO_x sensors?
6. Does the variability of the NO_x sensors change over time or by mode (after corrections for NO_x analyzer readings)?

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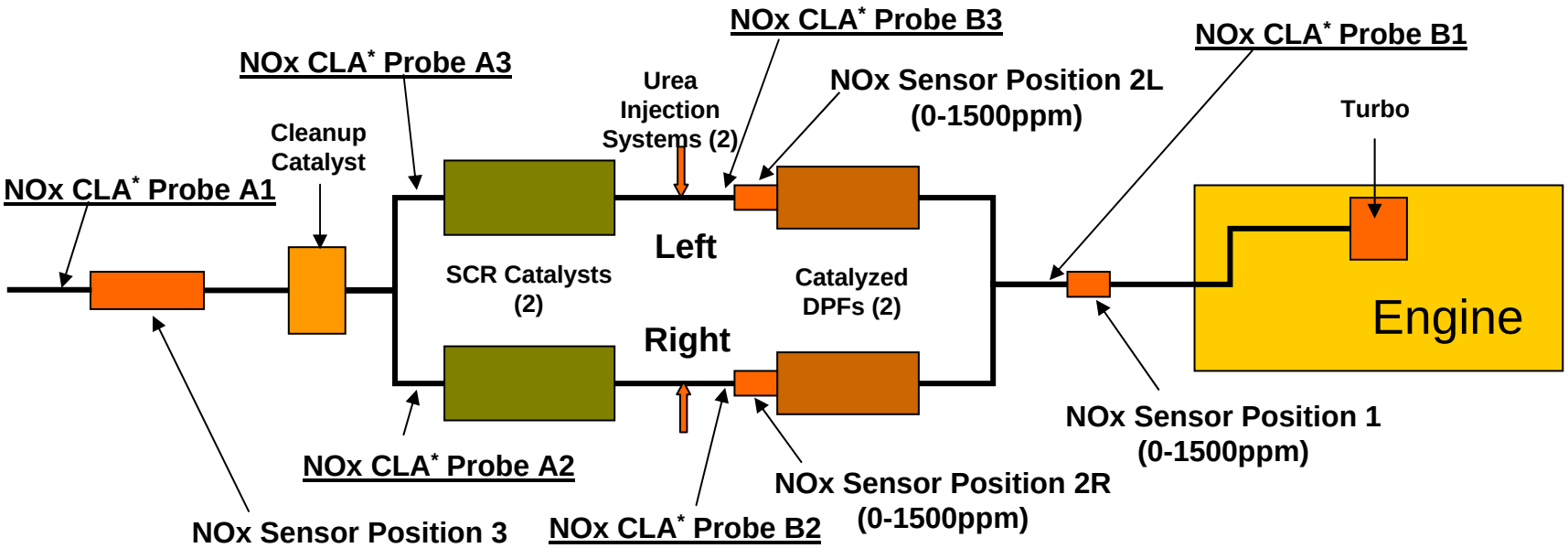
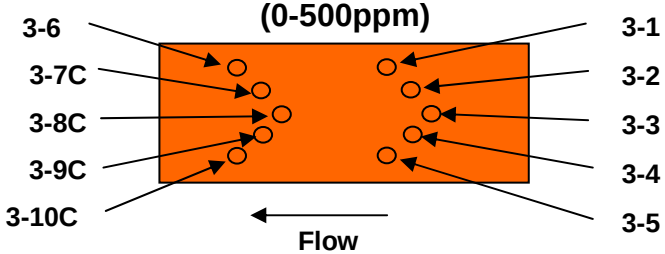
Methods

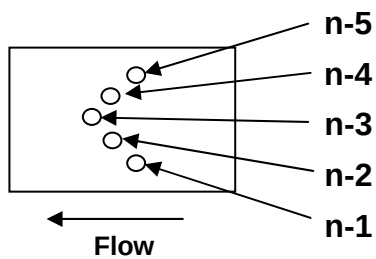
- 25 Sensors
  - Engine-out (5 sensors)
  - Post DPF, pre SCR (10 sensors – 5 per leg)
  - Post clean-up catalyst (6+4 sensors)
  - 21 with lab-grade electronics, 4 w/ production-grade
- Periodic Comparisons with Analyzer Readings
  - Measure at 13 ESC modes every 120 hours
  - 8 sets of comparisons every 1000 hours
- Independent Calibration Every 2,000 hours

Exhaust NO_x Instrumentation Layout





Detail for Positions 1, 2R, 2L



n = Location (see above)

Note: In each group of five, NO_x sensors are spaced evenly around top of pipe between "10 o'clock and 2 o'clock" positions

*CLA = Chemiluminescent Analyzer

Analysis Approach

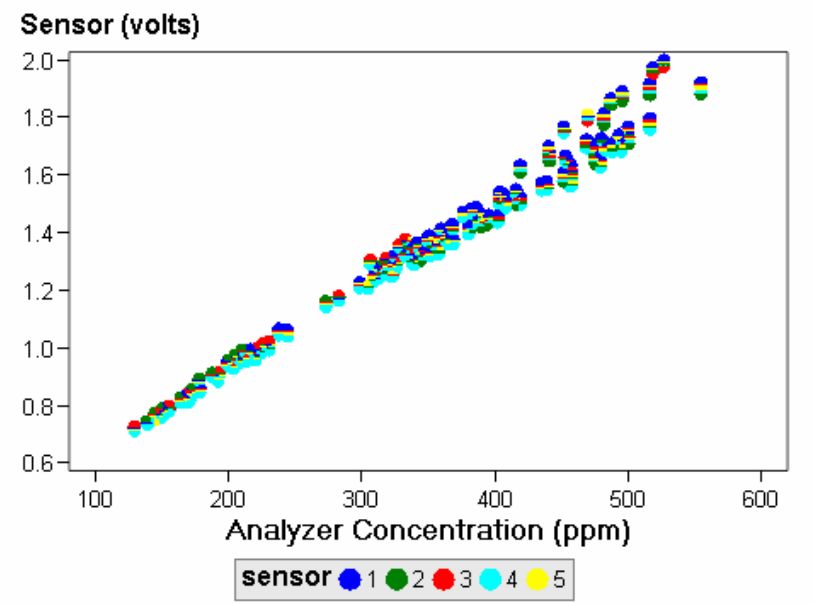
- Preliminary Analysis
  - Resolve data collection issues
- Fit Simple Linear Regression Model
  - Sensor Voltage = a + b*(analyzer ppm)
  - Evaluate deviations
    - By sensor, by mode, versus time
- Fit Multiple Regression Model
  - Volt = a + b*ppm + (time, sensor, mode effects & interactions)
  - Estimate mode effects and rates of change by sensor
- Confirm Results by Comparing Initial and 2,000-Hour Calibration Data

Overview of Findings - Durability Results

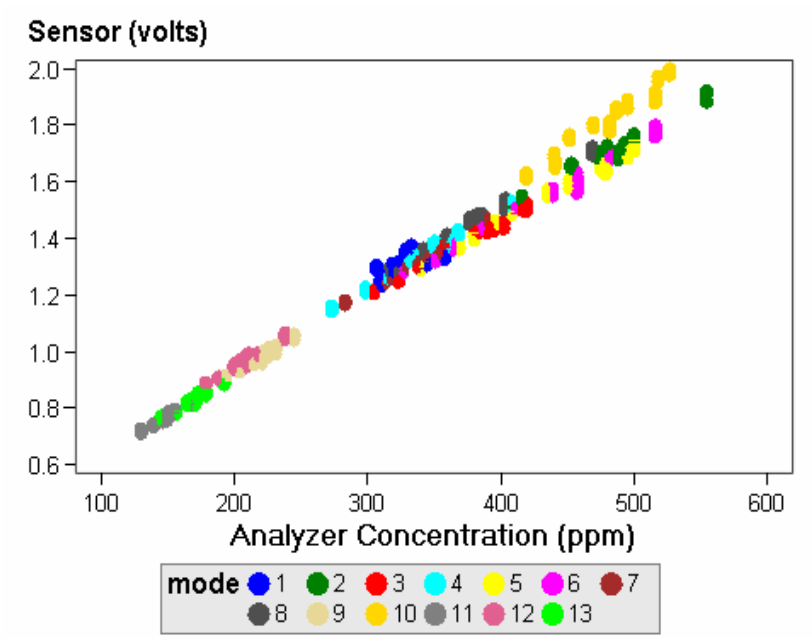
- Voltages from Pre-Catalyst Sensors (100-600 ppm)
  - Most (12 of 15) degraded by 3% to 4%
  - Three degraded by 5% to 7%
- Voltages from Post-Catalyst Sensors (10-200 ppm)
  - Most (8 of 10 sensors) had minimal degradation
  - One sensor (3-10C) did not operate properly (data not shown)
  - One (3-3) demonstrated low sensitivity at the start of testing and significant degradation (30%) over 2000 hours
- Cause of Failures and Degradation Unknown at This Time
  - Sensor problem?
  - Electronics?
  - Misconnection?
  - Installation?

Sensor Position 1:

Sensor Voltage vs. Analyzer ppm



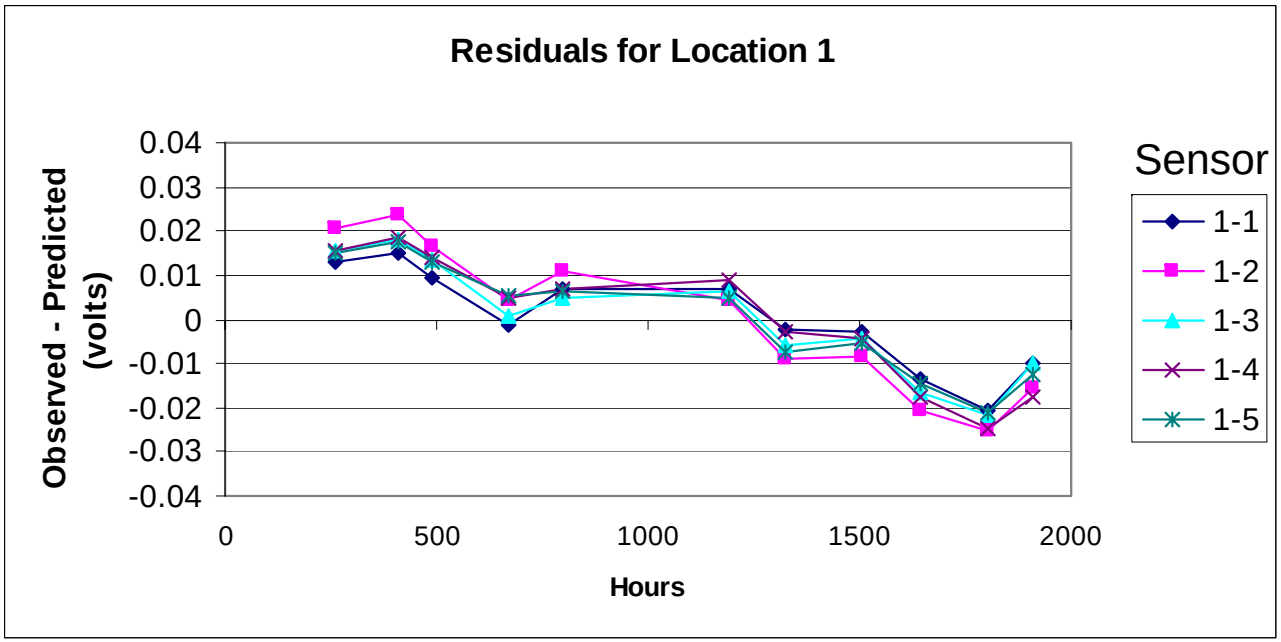
By Sensor



By Mode

Sensor Position 1:

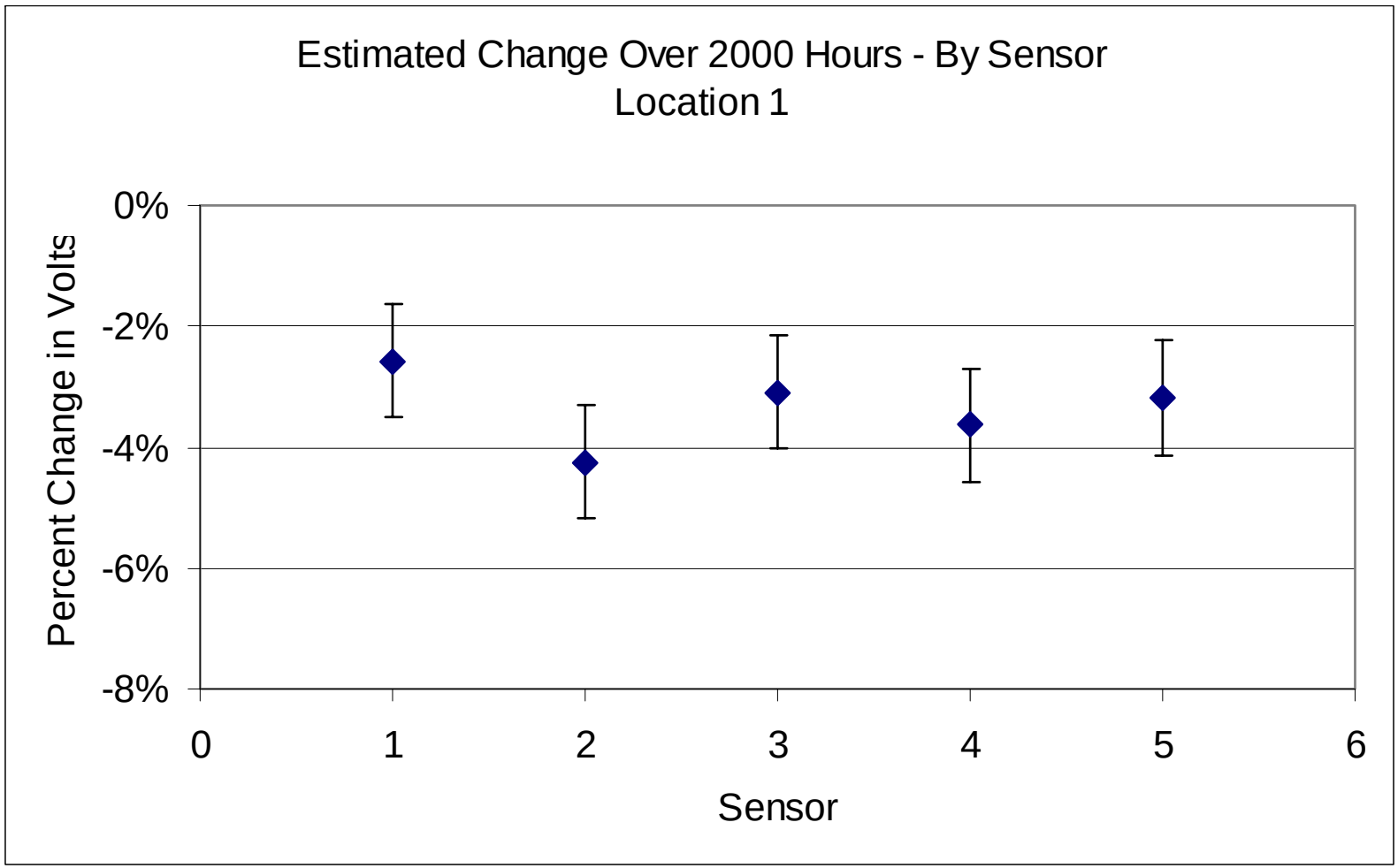
Residual (observed-predicted) vs. Time



- All sensors appear to degrade linearly
  - Approximately 4% change over 2,000 hours
- Slight variations in rates of change by sensor
  - Sensor No. 2 changing more quickly

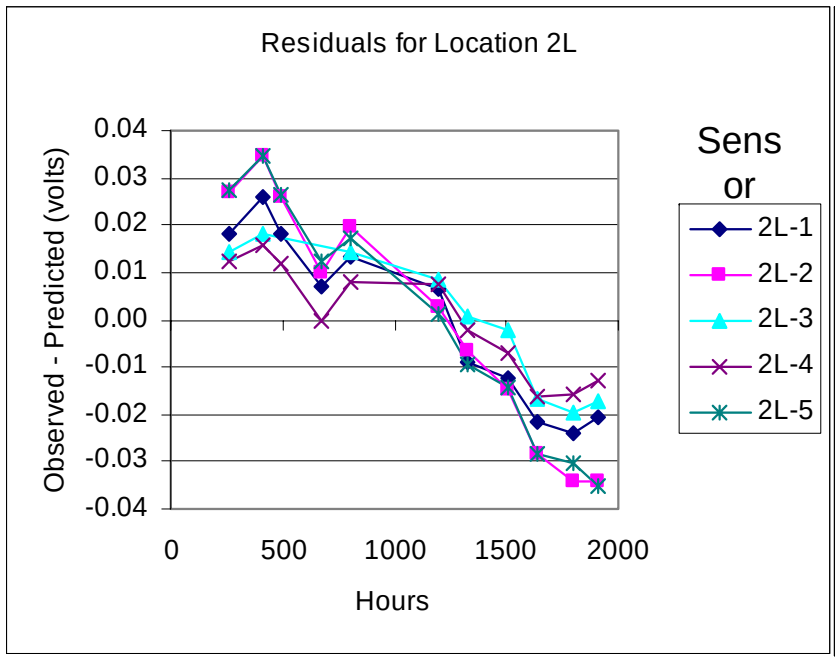
Sensor Position 1:

3% to 4% Change over 2000 hrs



Sensor Positions 2L, 2R:

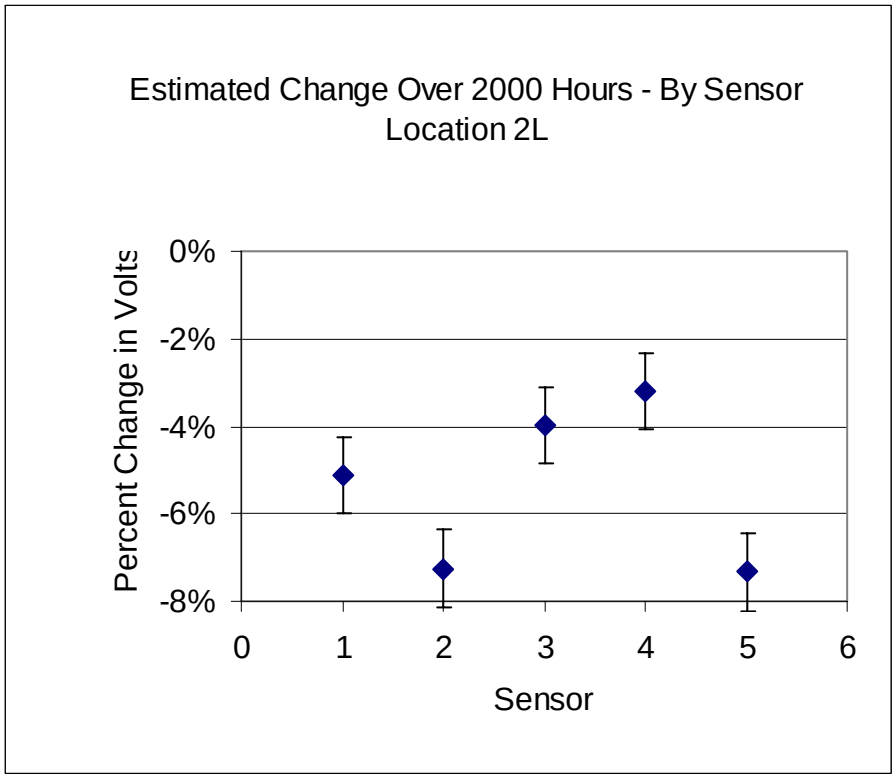
Residual (observed-predicted) vs. Time

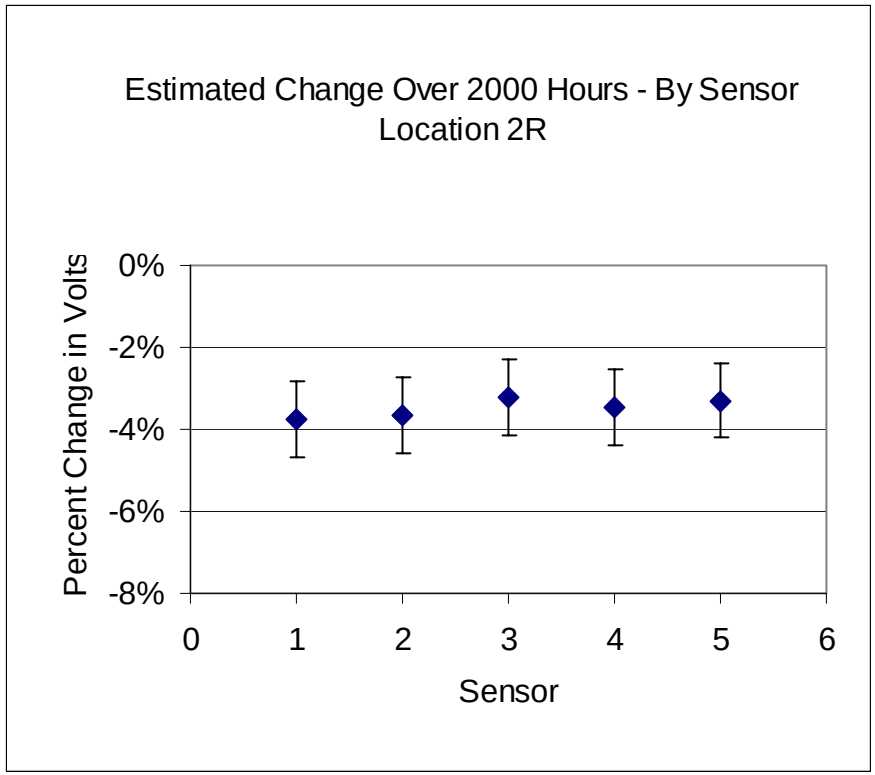


- Results generally similar to sensors in location 1
  - Approximately 4% change over 2,000 hours
- Three sensors in location 2L show higher degradation
  - Between 5% and 7% change over 2,000 hours

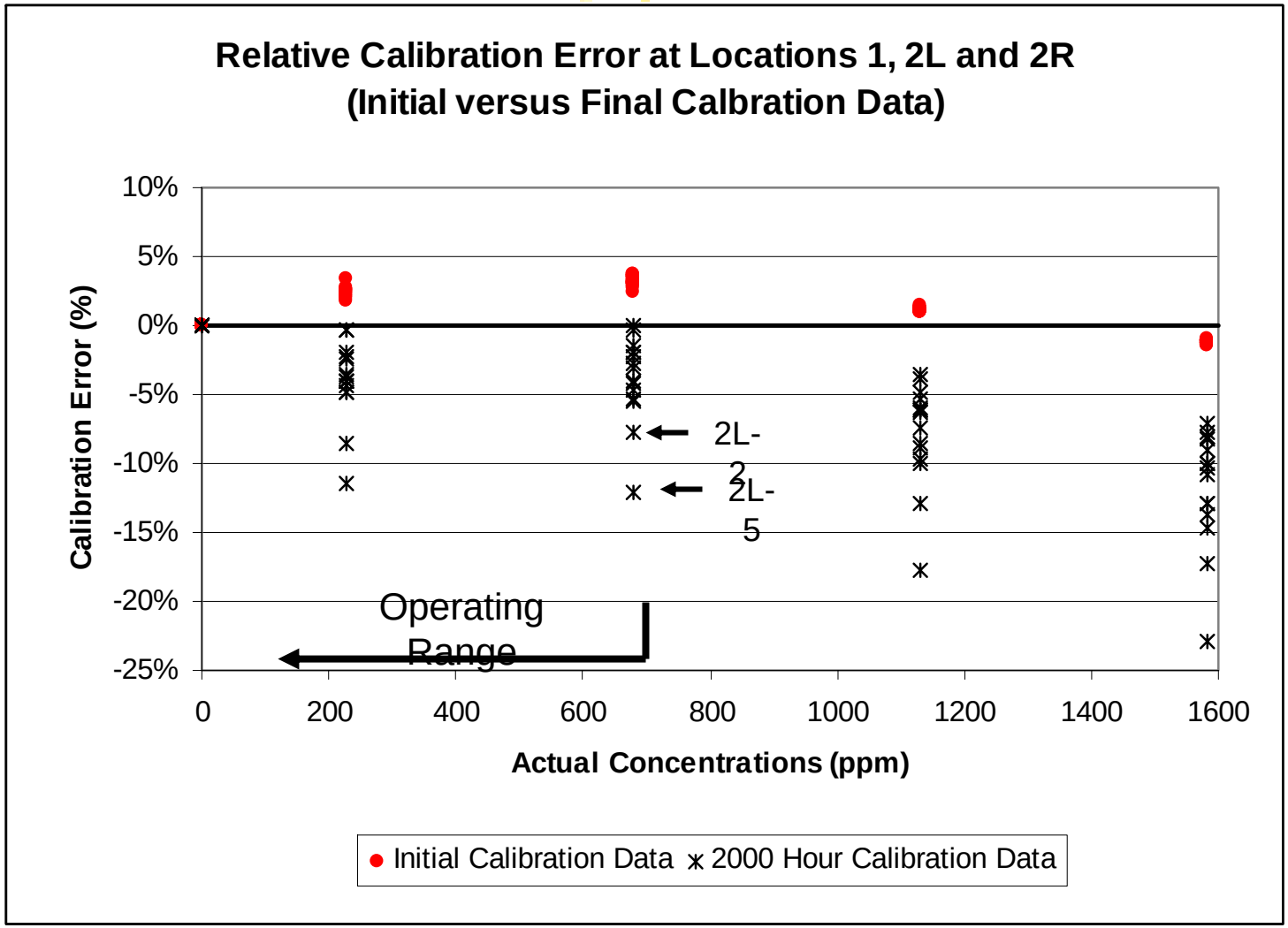
Sensor Positions 2L, 2R:

3% to 7% Change over 2000 hrs



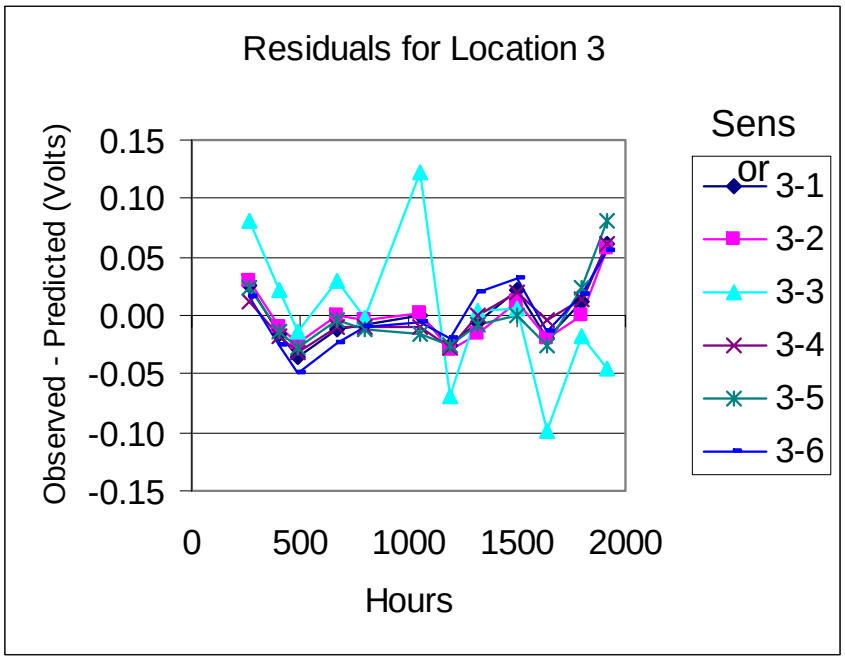


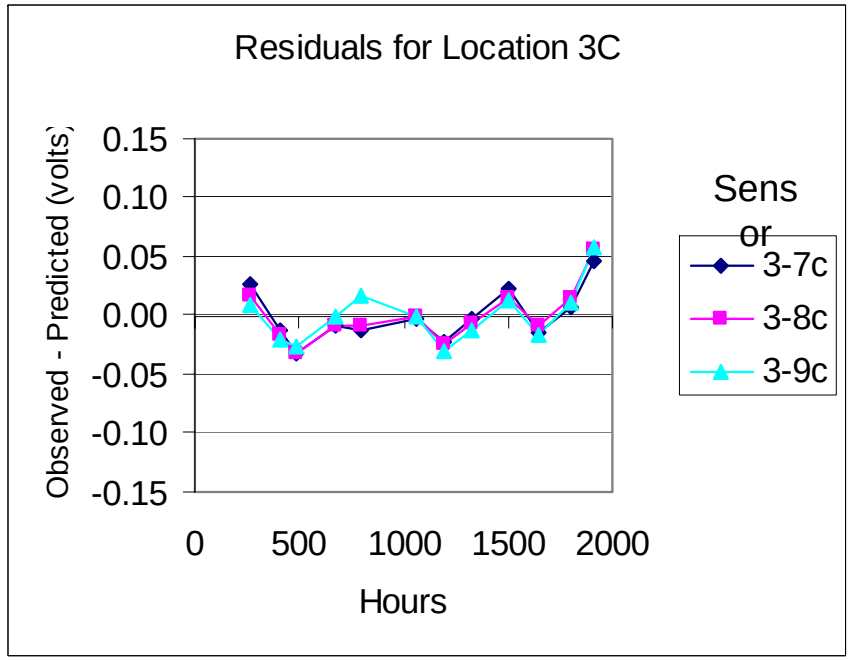
Initial vs. 2000-hr. Calibrations
(percent error from initial calibration)



Sensor Position 3:

Residual (observed-predicted) vs. Time

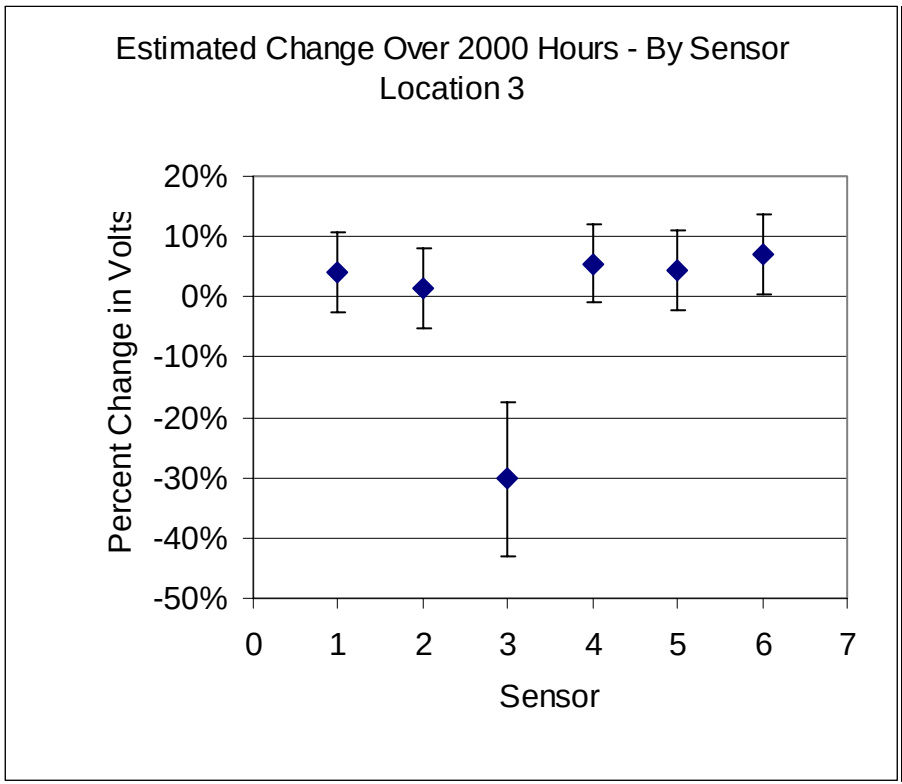


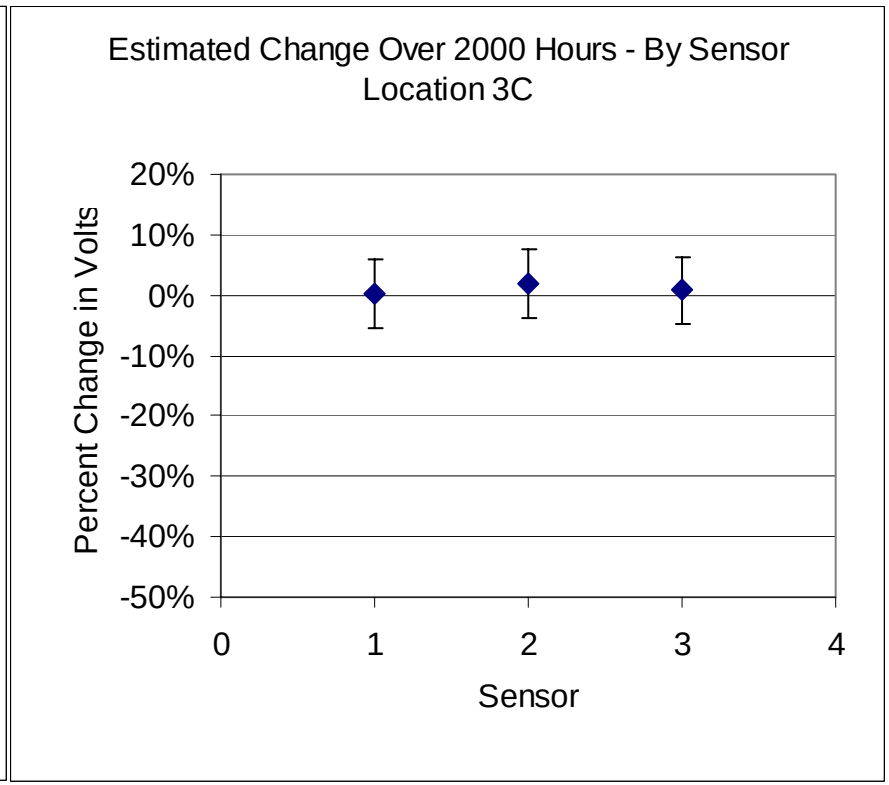


- Most sensors in location 3 show no significant degradation
- One sensor (3-3) shows more variability and degradation

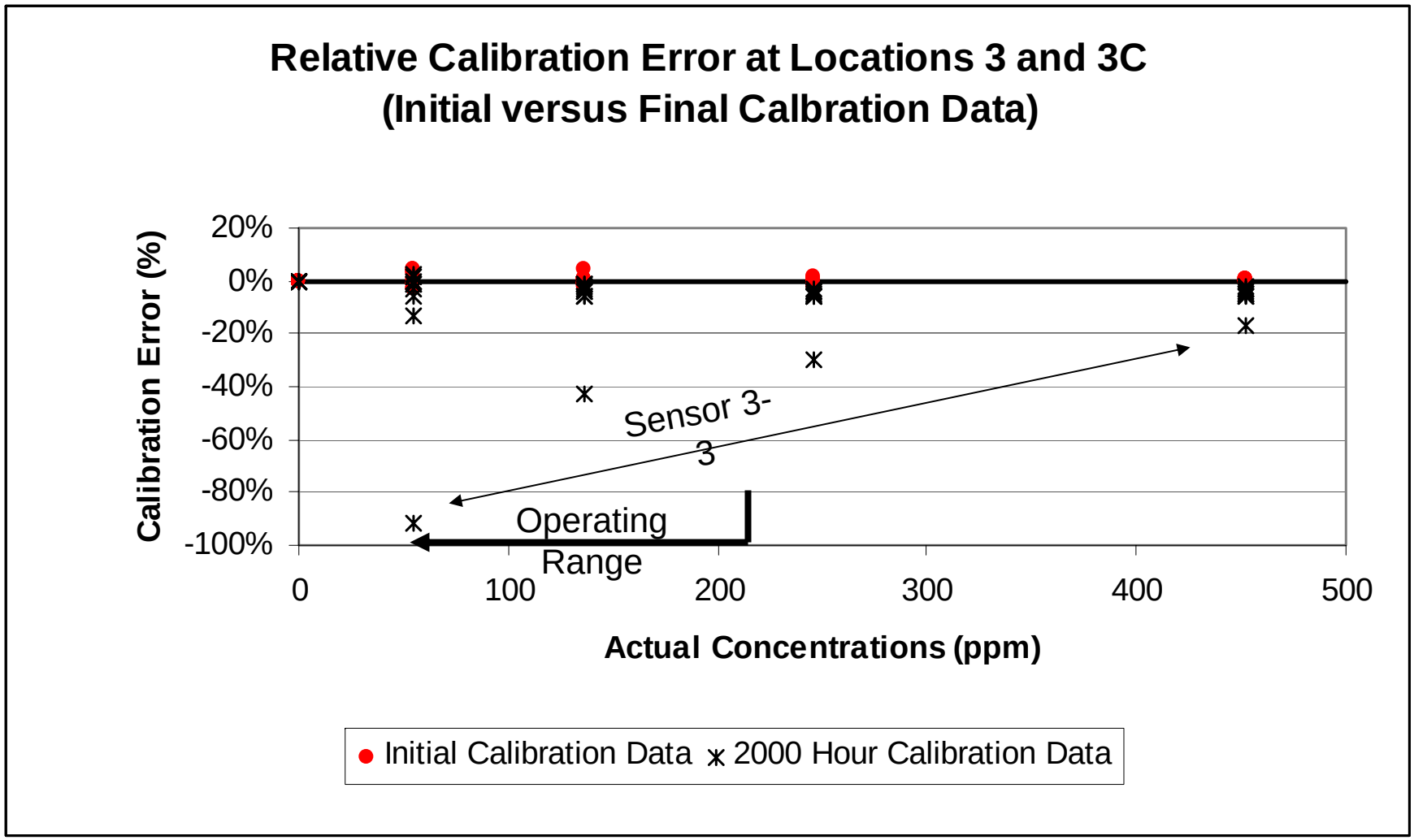
Sensor Position 3:

No Change – Except Sensor 3-3





Initial vs. 2000-hr. Calibrations
(percent error from initial calibration)

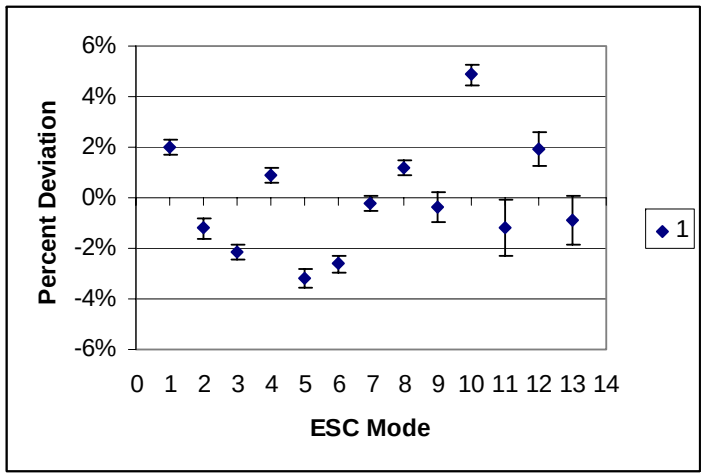


Overview of Findings
- Effects of Operating Mode

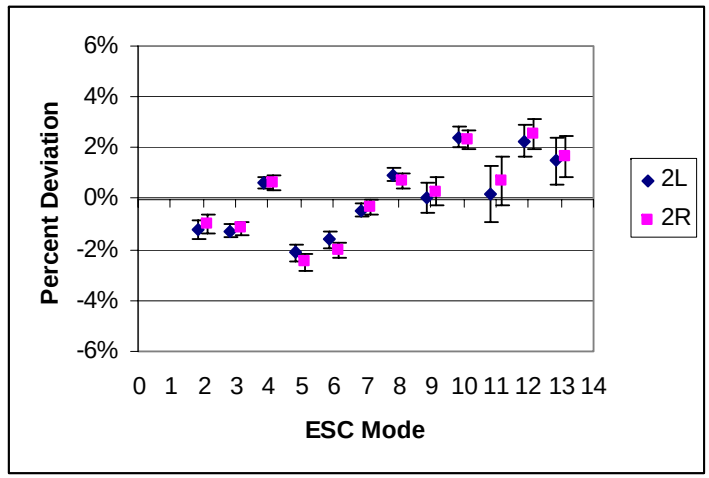
- Effects of Operating Mode on Sensor Calibration
  - Relative error due to operating mode is less than 4% at engine-out concentrations
  - Relative errors as high as 12% at lower concentrations
  - Possible adjustments based on speed and torque

Differences Among Modes – Relative to Calibration Curve

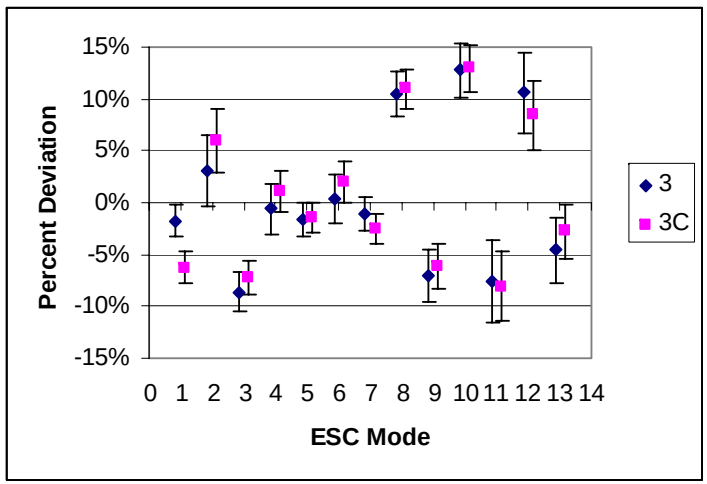
Location 1



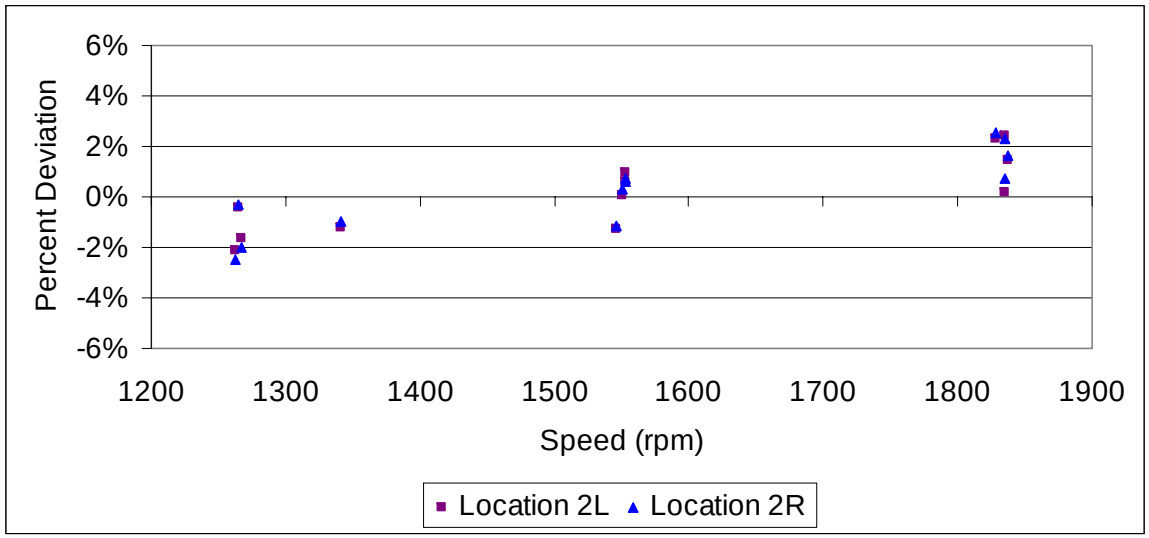
Locations 2L and 2R



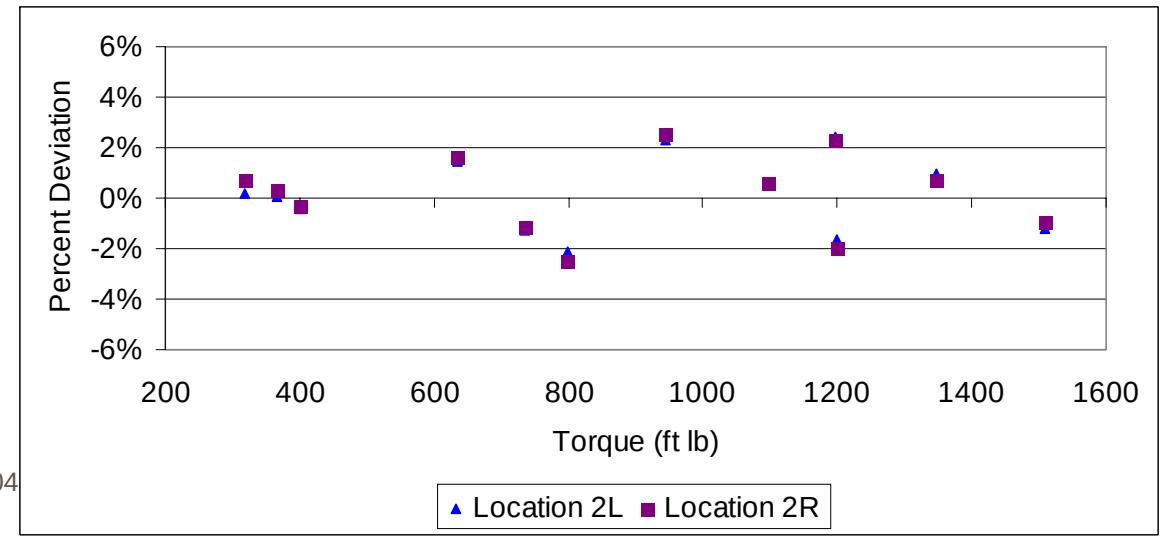
Locations 3 & 3C



Effects of Speed and Torque on Sensor Calibration



vs. Speed



vs. Torque

Preliminary Conclusions
(based on first 2000 hours of a 6000-hr test)

- On average, sensors used in pre-catalyst applications degrade linearly at a rate of 2% per 1,000 hours of operation
- Some degrade much faster
  - Investigation of failures is ongoing
- Calibration depends somewhat on operating mode.

Contact Information

John Orban, Ph.D.
Battelle
(614) 424-5773
orbanj@battelle.org

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